The Charm Renaissance: D-physics – a Selective Review

Guy Wilkinson
University of Oxford,
Denys Wilkinson Building,
Keble Road,
Oxford, OX1 3RH,
UNITED KINGDOM

1 Introduction

In recent years, no doubt because of the success of the B-physics programme at BaBar and Belle, charm has been considered the poor relation of heavy-quark physics. This is now changing: while B-physics remains the biggest show in town, it is no longer the *only* show. As will be argued, measurements in the D-sector have a vital, although indirect, role to play in pinning down the value of certain critical parameters of flavour-physics. Furthermore, the charm system provides a powerful laboratory in its own right to search for contributions from non-Standard Model (SM) processes.

Three main reasons can be identified which explain why charm physics is once more, quite correctly, being perceived as an important and exciting discipline:

1. **Precision CKM Tests**
   The success of the B-factories and the Tevatron has meant that CKM unitarity triangle tests are achieving successively higher levels of precision. This progress will continue with the LHCb experiment at CERN. Although the CKM elements being studied are those accessible in B-decays, charm turns out to be a vital ingredient in the programme.

2. **Charm Mixing and its Legacy**
   The discovery of $D^0 - \overline{D^0}$ oscillations has been the most exciting event of the past couple of years in high energy physics. The higher than expected rate is (arguably) intriguing in its own right, and points the way forward to searches for CP violation (CPV) in the charm sector.

3. **Recent Discoveries in Spectroscopy**
   The discovery of several missing charmonium states, and a number of unexpected and possibly exotic resonances (the X,Y and Z) has rekindled interest in the $c\bar{c}$ system as a laboratory for studying QCD.

In this review we focus on the first two topics. Useful discussion of the third item may be found in [1].

2 Facilities and Experimental Attributes

2.1 Overview

In reviewing the facilities which have contributed to charm physics studies in recent years, and are expected to do so in future, three complementary strands may be distinguished.

First are the fixed target experiments, most significantly those at Fermilab: E687, E791 and FOCUS. Second are the experiments located on e^+e^- machines. The majority of results have come from CLEO, BaBar and Belle, with the most important source of D-meson production being the e^+e^- contiuum lying under the $\Upsilon(4S)$. An important special case of e^+e^- operation is the threshold running pursued by CLEO-c at both the $\psi(3770)$ and at around 4170 MeV, where D_s mesons are produced. The significance of these threshold data is explained in more detail below. The BES-III [2] experiment is expected to follow the lead of CLEO-c, and accumulate perhaps 20 times more data over the coming decade. In the more distant future it is hoped that a Super-Flavour Factory [3] will be constructed, which will both increase the charm-from-contiuum sample of the B-factories by 1-to-2 orders of magnitude, and also have the ability to operate at very high luminosity at threshold.

The third important class of facility in which D-meson properties have been (and will be) studied is that of hadron colliders. The very high production cross-section gives rise to enormous statistics. The Tevatron, and CDF in particular, have published impressive studies exploiting the very large prompt D^* samples that are available. A recent CDF analysis [4] used this source to reconstruct around 3 million $D^0 \to K\pi$ events from 1.5 fb^{-1} of data. This programme will continue at LHCb, where the possibilities of harnessing secondary charm from B-decays has also been explored and shown to be very promising [5]. Plans are being made for an upgraded LHCb experiment [6] which will run at around 10 times the luminosity, and have more efficient triggering, which will therefore provide still larger datasets.

2.2 Threshold Running and CLEO-c

Threshold running at e^+e^- machines has several attractive characteristics:

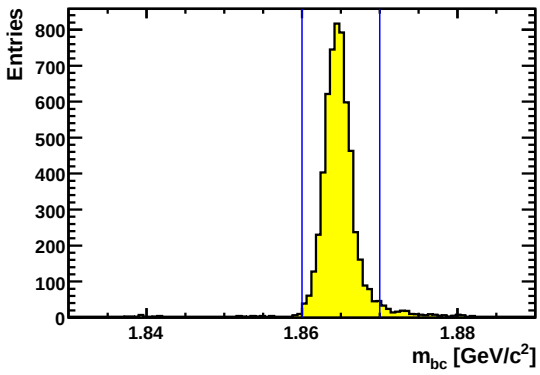

Figure 1: Beam constrained invariant mass of CLEO-c $D^0 \to K^-\pi^+\pi^-\pi^+$ events in which the other meson has been reconstructed as $K^+\pi^-$. (The tail at high mass arises from signal events in which there has been significant ISR.)

- The environment is very clean, with no additional fragmentation particles produced. This allows for very low backgrounds, particularly in the case where both D-mesons are reconstructed. Figure 1 shows the beam constrained mass plotted in events where one mesons has been reconstructed in the $K\pi\pi\pi$ and the other as $K\pi$. The background is at the level of 1%.

- Quantum correlation exists between the two D mesons which can be exploited. For example, at the $\psi(3770)$ the quantum numbers of the resonance mean that if one D meson is reconstructed in a CP-even state, for example K^+K^-, then the CP of the other state is known to be CP-odd. This ability to *CP-tag* decays is the most valuable feature of threshold running, the application of which is explained in Sec. 3.

- If all charged particles and photons are reconstructed then kinematical constraints allow the the presence of neutral particles to be inferred, such as K^0_L mesons and neutrinos. This is useful as it allows CP-tags such as $K^0_L\pi^0$ to be included in double-tag analyses, and enables the reconstruction of leptonic decays such as $D^+_s \to l^+\nu$.

CLEO-c, which completed operation in Spring of this year, accumulated 818 pb^{-1} of data at the $\psi(3770)$ and 586 pb^{-1} at $\sqrt{s} = 4170$ MeV.

2.3 Experimental Attributes

The desirable attributes needed for a successful D-physics experiment are essentially the same as those required in B-physics studies. These include efficient tracking and, if

possible, good calorimetry suitable for γ and π^0 reconstruction, hadron identification capabilities to permit π-K discrimination, and – in a hadron collider environment – a trigger system sensitive to the final states of interest. The results discussed in this review come primarily from BaBar, Belle, CLEO-c and CDF – experiments which possess most or all of these characteristics.

3 D Decays and the CKM Unitarity Triangle

Our understanding of CP-violating phenomena, as expressed in the context of the Standard Model, is most usefully represented by constraints in the $(\overline{\rho}, \overline{\eta})$ plane, where at order λ^2, these symbols represent two of the parameters of the CKM-matrix in the Wolfenstein parameterisation [8] multiplied by the factor $(1 - \lambda^2)$, λ being the sine of the Cabibbo angle. All these constraints (with the exception of ϵ_K, the CP-violating parameter obtained from kaon decays) come from measurements of B-meson properties, which are expected to map out a triangle with vertices $[(0,0),(1,0),(\overline{\rho},\overline{\eta})]$ The present experimental status is summarised in Fig. 2. All measurements are broadly consistent with each other, indicating the validity of the CKM paradigm. Nonetheless, new physics contributions are not excluded and may become apparent when the experimental precision improves still further – this is one of the principal goals of the flavour physics programme. In surveying where improvement is necessary it is natural to focus on both the angle γ, indicated in Fig. 2, and the so-called 'mixing' side opposite to this angle. The geometry of the triangle means that these two quantities are closely linked, for it is the length of the side which largely determines the expected value of γ. Two possible central values are predicted for the value of γ at the one sigma level: $(55.4^{+2.5}_{-2.2})^\circ$ or $(67.4^{+3.3}_{-5.6})^\circ$ [7]. Comparison of the measured and expected values of γ is a powerful way to search for new physics. For both quantities it will be seen that, despite the fact that both of these features are measured in B-decays, crucial input is provided by analyses of D-decay properties.

3.1 The CKM Angle γ and D-decays

The most powerful manner in which to measure the angle γ is with $B^\pm \to DK^\pm$ decays. Here two tree diagrams contribute, one of which involves a D^0 meson and the other a $\overline{D^0}$ meson. If a final state is chosen which is common to both D^0 and $\overline{D^0}$ then interference occurs that includes terms dependent on the phase difference between the diagrams, which is $\delta_B - \gamma$, where δ_B is a CP-conserving strong phase. Comparing suitable observables between B^- and B^+ decays allows γ and δ_B to be determined, along with r_B, a parameter which represents the relative strength of the two diagrams (≈ 0.1). Categories of D-decays which have been proposed for these measurements include CP-eigenstates [9], for example K^+K^- or $K^0_S\pi^0$, Cabibbo favoured

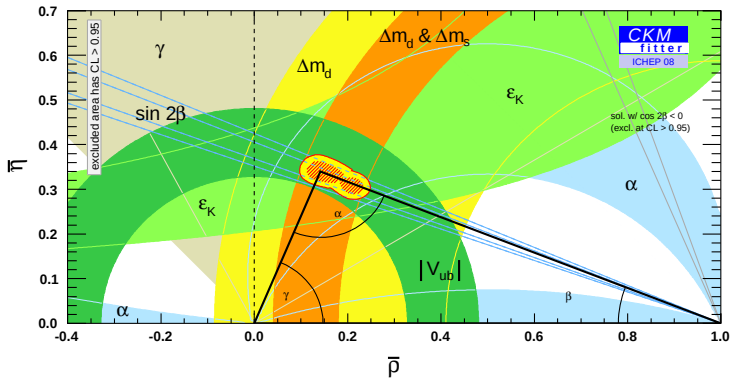

Figure 2: Constraints in the $\overline{\rho}, \overline{\eta}$ plane as of Summer 2008 [7].

and doubly-Cabibbo suppressed decays (the so-called 'ADS' approach [10]), for example $K^-\pi^+$ or $K^-\pi^+\pi^-\pi^+$, and self-conjugate multibody states, such as $K^0_S\pi^+\pi^-$ [11]. It is this latter method which has yielded the best constraints on γ with the statistics presently available at the B-factories [12, 13].

In using $D^0 \to K^0_S\pi^+\pi^-$ decays in a $B^\pm \to DK^\pm$ analysis the CP-sensitive observable is the Dalitz plot of the D-decay. A non-zero value of γ will give rise to differences in the distributions for B^+ and B^- decays. Examples plots from a recent BELLE analysis [13] are shown in Fig. 3. If the composition of the intermediate resonances involved in the D-decay is understood, then a comparison of the two plots allows γ to be extracted through an unbinned likelihood fit. In this manner charm physics provides a critical input to the γ measurement.

The B-factory experiments have devoted a great deal of effort to modelling the $D^0 \to K^0_S\pi^+\pi^-$ decay for the purposes of the γ measurement. A recent BaBar study [12] has used a sample of 487k flavour tagged $D^{*\pm} \to D\pi^\pm$ events to which an isobar model involving ten resonances is fitted. The $\pi\pi$ and $K^0_S\pi$ S-wave contributions are described with a K-matrix [14] and LASS [15] parametrisation respectively. Projections of the Dalitz plot, with the model fit superimposed, are shown in Fig. 4. The χ^2 of the fit is 1.11 for 19274 degrees of freedom. In the γ fit a systematic uncertainty is incurred arising from how well this model represents reality. This error is assigned to be 7°, which is small compared with the statistical uncertainty, but will become limiting with the higher statistics B-samples expected at LHCb.

An alternative approach is to make a binned fit in which the model predictions are replaced by quantities which are directly measured in double-tagged quantum-correlated D-decays at the $\psi(3770)$ [16]. If one D-meson is reconstructed in a CP-eigenstate then the other meson will be in the opposite eigenstate, that is a known superposition of D^0 and $\overline{D^0}$. So if this meson is reconstructed as $K^0_S\pi^+\pi^-$ then there

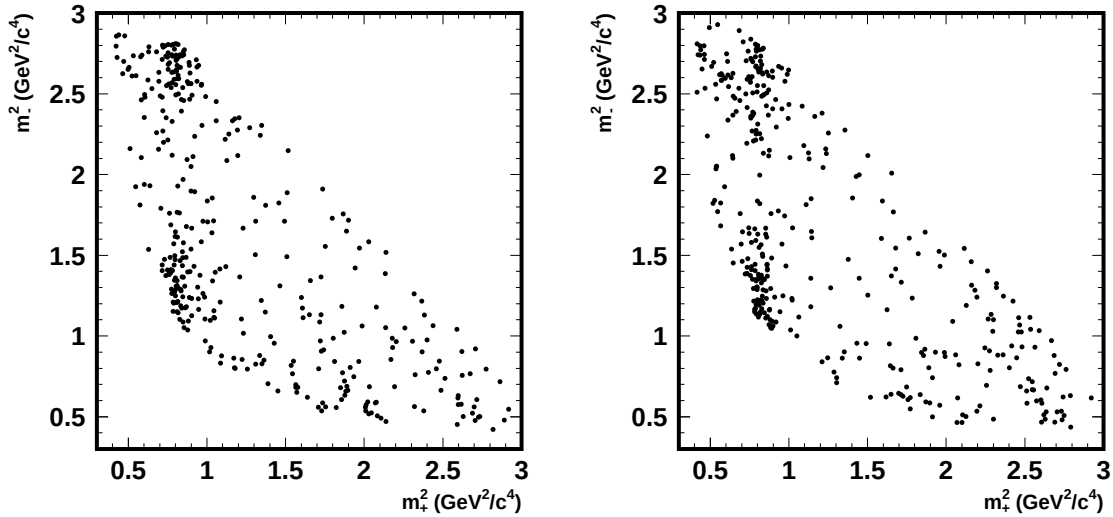

Figure 3: Dalitz plots of $D^0 \to K^0_S\pi^+\pi^-$ decays arising from the process $B^\pm \to DK^\pm$ [13]. Left: B^-; right: B^+. The horizontal axis is the invariant mass squared for the $K^0_S\pi^+$ pair, and that of the vertical axis the same for the $K^0_S\pi^-$.

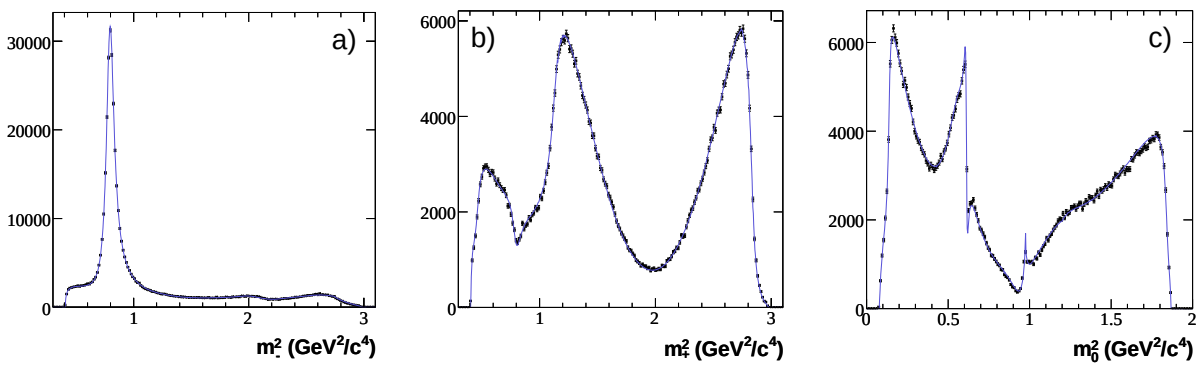

Figure 4: BELLE projections of the Dalitz variables for the decay $D^0 \to K^0_S\pi^+\pi^-$ with fit result superimposed [12]. Invariant mass squared for the: $K^0_S\pi^-$ (a), the $K^0_S\pi^+$ (b) and the $\pi^+\pi^-$ (c).

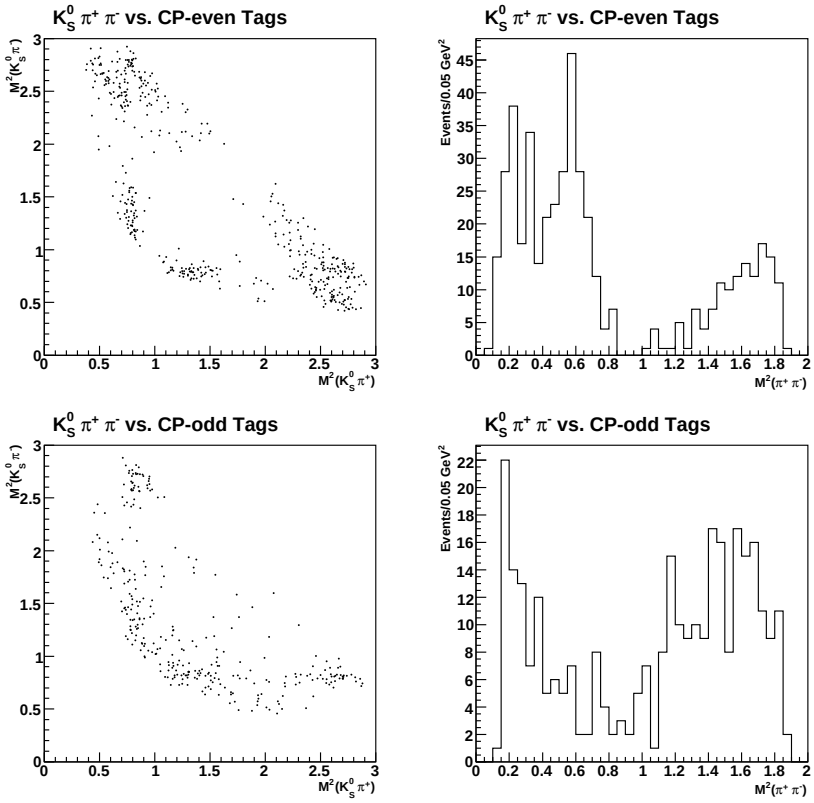

Figure 5: CP-tagged $D^0 \to K^0_S\pi^+\pi^-$ Dalitz plots and $\pi^+\pi^-$ projections from CLEO-c.

will be contributions from D^0, $\overline{D^0}$ and an interference term involving the strong phase difference between the two decay paths. It is this information which is invaluable in the γ measurement and is inaccessible through direct means in flavour-tagged D-decays. Similarly useful input comes from events containing two $K^0_S\pi^+\pi^-$ decays. Quantities required for the γ extraction (the so-called c_i and s_i coefficients – see [16]) are measured which are directly related to the relative population of the chosen bins for different combinations of tags. Figure 5 shows $K^0_S\pi^+\pi^-$ Dalitz plots and the corresponding projections made with CLEO-c data for CP-even and CP-odd tags. The difference in structure is apparent, for example the absence of the $K^0_S\rho^0$ peak in the events containing a CP-odd tag. Preliminary results exist from CLEO-c [17]; the finite $\psi(3770)$ sample size will induce a residual error of $1-2^\circ$ on γ. Although the binned treatment leads to some degradation in B-statistical precision, it is still expected at LHCb that this model independent approach will outperform the model dependent fit after one-year (2 fb^{-1}) of data-taking [20], with an error dominated by measurement uncertainties alone.

There are other equally important ways in which quantum-correlated D-decays

can be harnessed for the $B^{\pm} \to DK^{\pm}$ γ analysis, and which are being explored on CLEO-c. These include determinations of the strong phase difference in $D^0 \to K-\pi^+$ decays [18], and the *coherence factor* [19] and average strong phase difference in $D^0 \to K^-\pi^+\pi^-\pi^+$ and $D^0 \to K^-\pi^+\pi^0$ decays [21], all of which are important for the ADS family of γ measurements.

An average of existing measurements with B-data yields $\gamma = (67^{+32}_{-25})^\circ$ [7]. LHCb has the potential of reducing this uncertainty to $2-3^\circ$ [22], using a combination of methods, the majority of which will rely critically on the knowledge of the D-meson decay structure.

3.2 The 'Mixing Side' and D-Meson Tests of Lattice QCD

The ratio $|V_{td}/V_{ts}|$ can be used to fix the unitarity triangle side opposite to the angle γ. This ratio is determined from the ratio of oscillation frequencies Δm_{B_s} to Δm_{B_d} in the B^0 and B_s systems:

$$|V_{td}/V_{ts}| = (f_{B_s}\sqrt{B_{B_s}})/(f_{B_d}\sqrt{B_{B_d}})\sqrt{(\Delta m_{B_d}\, m_{B_d}/\Delta m_{B_s}\, m_{B_s})}. \quad (1)$$

Also involved are the meson masses, $m_{B_{d(s)}}$, the meson decay constants $f_{B_{d(s)}}$ and the bag factors $B_{B_{d(s)}}$. The ratio $(f_{B_s}\sqrt{B_{B_s}})/(f_{B_d}\sqrt{B_{B_d}})$ is calculated in lattice QCD [23] to be 1.23 ± 0.06. It is the uncertainty in this calculation which dominates the knowledge of the length of the side, and hence the prediction for the expected value of γ. For this reason, it is highly desirable to make experimental validations of the lattice QCD calculations. This cannot readily be done in the B-system, but it is possible to make measurements of f_D and f_{D_s}, the form factors for D^+ and D_s decays. Comparison between these results and the lattice calculations then provide a critical test of the lattice approach.

The D^+ and D_s^+ form factors may be measured from leptonic meson decays. The partial width for a D^+ decaying to $l^+\nu$ is given by

$$\Gamma(D^+ \to l^+\nu) = \frac{1}{8\pi} G_F^2 f_D^2 m_l^2 m_D \left(1 - \frac{{m_l}^2}{{m_D}^2}\right)^2 |V_{cd}|^2 \quad (2)$$

and similarly for D_s^+, but here involving the parameters f_{D_s}, m_{D_s} and $|V_{cs}|$. If the values for the magnitudes of the CKM angles are taken from elsewhere, the form factors may be extracted. Measurements of f_{D_s} come from CLEO-c [24, 25], BELLE [26] and BaBar [27], and a recent new determination of f_D has been made by CLEO-c [28]. These are to be compared with the most precise available lattice calculation from [29].

The CLEO-c measurements are based on full-reconstruction techniques which exploit the cleanliness of the threshold environment. In the f_D analysis, for example, events are considered from the $\psi(3770)$ running where one charged D meson is found together with a single other charged track, which is minimum ionising. The missing

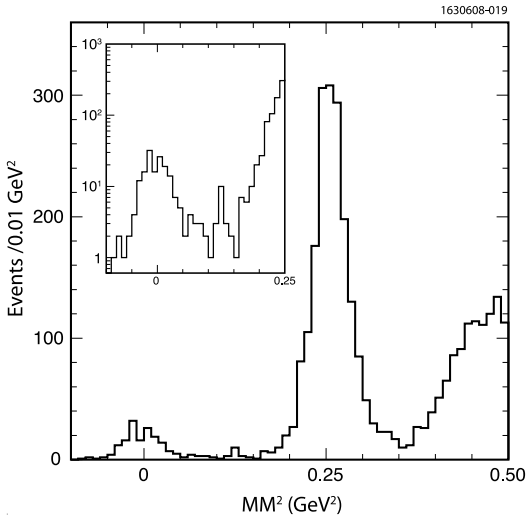

Figure 6: Missing mass squared in the CLEO-c $D^+ \to \mu\nu$ analysis [28].

mass for these events is shown in Fig. 6. A peak is seen at zero-missing mass, consistent with $D^+ \to \mu^+\nu$ events and clearly separated from the background process $D^+ \to K^0\pi^+$. A small contribution is seen between these two peaks coming from $D^+ \to \tau^+(\pi^+\overline{\nu})\nu$. Using the population of this peak to measure the branching ratio yields a result $BR(D^+ \to \mu^+\nu) = (3.82 \pm 0.32 \pm 0.09) \times 10^{-4}$ and a form-factor value which is $f_D = (205.8 \pm 8.5 \pm 2.5)$ MeV (this result is with the ratio of $\tau^+\nu$ and $\mu^+\nu$ decays fixed to the Standard Model expectation) [28]. Similar methods are used for the f_{D_s} measurement at CLEO-c based on the 4170 MeV dataset, using both muon and tau decays [24, 25]. In [24] $D_s^+ \to \mu + \nu$ and $\tau^+(\pi^+\nu)\nu$ decays from 314 pb^{-1} of data are used to determine $B(D_s^+ \to \mu^+\nu) = (8.00 \pm 1.3 \pm 0.4) \times 10^{-3}$ and $f_{D_s} = (274 \pm 13 \pm 7)$ MeV.

At the B-factories the procedure is first to infer the presence of a D_s^+ from the recoiling mass seen against the system of a reconstructed D and fragmentation particles, and then to look for a muon and compute the invariant mass of what remains. With 548 fb^{-1} of data Belle have measured $B(D_s^+ \to \mu^+\nu) = (6.44 \pm 0.76 \pm 0.57) \times 10^{-3}$, implying a form factor result of $f_{D_s} = (275 \pm 16 \pm 12)$ MeV.

The CLEO result for f_D is in agreement with the lattice calculation of $f_D = 207 \pm 4$ MeV [29]. The experimental results for f_{D_s} are consistent with each other and give a result of $f_{D_s} = 270 \pm 8$ MeV, which is three sigma above the lattice value of $f_{D_s} = 241 \pm 3$ MeV. This is an intriguing situation, which could possibly hint at problems in the lattice approach, or even new physics contributions to the D_s decay [30]. It is therefore imperative to improve still further the experimental precision. New results for f_{D_s} are expected soon from CLEO-c with the full 4170 MeV

dataset. Updates are also possible from BaBar and Belle. BES-III data will allow for improved measurements of both f_{D_s} and f_D.

It is also possible to measure semi-leptonic form factors in D decays [31], which then allow for another test of lattice QCD predictions.

4 Searches for New Physics in Charm Mixing and Decays

The recent discovery of mixing in the D^0 system, after 30 years of experimental effort, is a significant milestone in flavour physics. Here a very brief summary is given; a full review can be found elsewhere at this conference [32]. Attention is now turning to the search for CP violation in the charm sector, which is an outstanding method to probe for evidence of contributions from non-SM processes. Rare charm hadron decays, although not in general allowing for the cleanliness of interpretation that is familar in B-physics, constitute another area in which beyond-the-SM physics may manifest itself. It must be emphasised that the processes discussed here, suppressed or forbidden in the SM, offer a complementary route to the search for new physics to those pursued elsewhere in flavour physics. In contrast to the kaon and B-meson sectors, rare charm transitions are unique in receiving contributions from loop diagrams involving virtual down-type quarks.

4.1 Charm Mixing and CP Violation

$D^0 - \overline{D^0}$ transitions are governed by the two parameters

$$x = \frac{\Delta M}{\Gamma} \quad \text{and} \quad y = \frac{\Delta\Gamma}{2\Gamma}, \tag{3}$$

where ΔM and $\Delta\Gamma$ are the mass and width differences respectively between the two mass eigenstates, and Γ the mean width of these eigenstates. Mixing can be mediated by short or long-distance processes. GIM suppression and the values of the relevant CKM elements make the short-distance contributions tiny in the Standard Model. Box diagrams alone are expected to lead to values of $x \sim 10^{-5}$ and $\sim 10^{-7}$ [33]. Long distance effects can however be sizable, particularly for y where they are expected to be dominant, and able to enhance these values by many orders of magnitude. The only clear signature of new physics therefore would be the observation $x >> y$.

Since 2006 the B-factories have produced results of high precision in a range of complementary strategies sensitive to $D^0 - \overline{D^0}$ mixing. These have included searches for mixing in the interference between Cabibbo-favoured and doubly-Cabibbo suppressed decays [34] (with an impressive result in the same analysis also emerging from the Tevatron [4]), measurements of the lifetime in decays to CP-eigenstates [35],

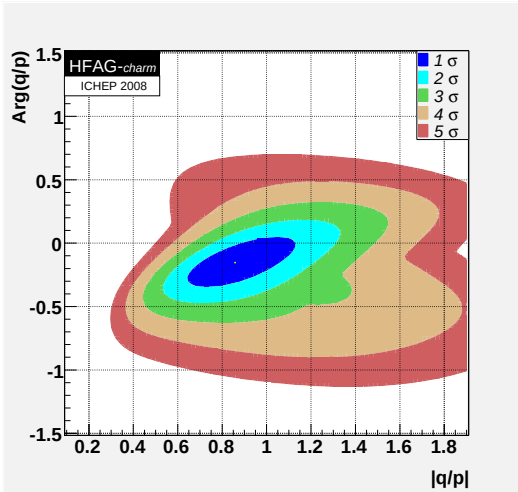

Figure 7: World average results for $|q/p|$ and ϕ [37].

and mixing-sensitive amplitude analyses of $D^0 \to K^0_S\pi^+\pi^-$ decays. Although no single measurement has yet yielded a five-sigma discovery in isolation, the cumulative evidence is beyond doubt. A global fit of all results (allowing for CPV) excludes the no-mixing hypothesis at 9.8 σ and yields parameter values of $x = 1.00^{+0.24}_{-0.26}$ and $y = 0.76^{+0.17}_{-0.18}$ [37]. Although these values are larger than many commentators expected [38], they remain in accordance with SM expectations. Nevertheless, the absence of a clear indicator of beyond-the-SM effects can be used to set constraints on a host of new physics models [39]. Furthermore, the larger-than-anticipated value of the oscillation parameters is encouraging in the search for mixing-related CPV.

An unambiguous signature of the existence of new physics processes would be the discovery of CPV, either in the mixing, or in the interference between mixing and decay. The former effect is characterised by a non-zero value of $\epsilon = |q/p| - 1$, and the latter by a finite value of $\phi = \arg(q/p)$, where q and p are the coefficients which relate the mass ($|D_{1,2}>$) and flavour ($|D^0>$, $|\overline{D^0}>$) eigenstates: $|D_{1,2}> = p|D^0> \pm q|\overline{D^0}>$. In the SM both ϵ and ϕ are negligibly small [40]. Sensitivity to these parameters is achieved by merely generalising the fits of the mixing analyses to allow for CPV contributions. A global average of the present results, displayed in Fig. 7, shows no indication of CPV, with one sigma uncertainties on ϕ and ϵ of 0.13 and 0.16 respectively [37]. This precision is already an impressive achievement given the short history of D^0-mixing studies. Improvements at LHCb and future facilities are eagerly anticipated.

One may look for the effects of direct CPV in a final state f by searching for

Mode	BaBar	BELLE	CLEO
K^+K^-	$0.00 \pm 0.34 \pm 0.13$ [42]	$-0.43 \pm 0.30 \pm 0.11$ [43]	
$\pi^+\pi^-$	$-0.24 \pm 0.52 \pm 0.22$ [42]	$0.43 \pm 0.52 \pm 0.12$ [43]	
$K^+K^-\pi^0$	$1.00 \pm 1.67 \pm 0.25$ [44]		
$\pi^+\pi^-\pi^0$	$0.62 \pm 1.24 \pm 0.28$ [44]	$0.43 \pm 0.41 \pm 1.23$ [45]	
$K^+K^-\pi^+$			$-0.03 \pm 0.84 \pm 0.29$ [46]

Table 1: Recent results in percent for A^f_{CP} in singly-Cabibbo suppressed D decays. The uncertainties are statistical and systematic respectively.

non-zero values of the asymmetry A^f_{CP}:

$$A^f_{CP} = \frac{\Gamma(D \to f) - \Gamma(\overline{D} \to \overline{f})}{\Gamma(D \to f) + \Gamma(\overline{D} \to \overline{f})}. \tag{4}$$

In the case that the decaying meson is a D^0 then the result includes possible contributions from mixing and mixing-induced CPV, as well as the direct component. Singly-Cabibbo suppressed decays are the most interesting place to look for direct CPV, as gluonic penguins lead to the possibility of significant effects (up to 10^{-2}) from many new physics models [41], and indeed to non-negligible contributions from the SM itself [40].

Recently there have been results [42, 43, 44, 45, 46] which are achieving sub-percent precision on measurements of A^f_{CP} for singly-Cabibbo suppressed decays. These results are summarised in Table 1. Although all results are consistent with zero CPV, it is clear that experiments are now entering a very interesting regime. Figure 8 shows the D^0 and $\overline{D^0}$ mass peaks from the BaBar K^+K^- and $\pi^+\pi^-$ analyses, which have around 130k and 64k signal events respectively. What is impressive about these analyses is the manner in which the systematic uncertainties have been controlled. In the B-factory K^+K^- and $\pi^+\pi^-$ analyses [42, 43], for example, $D^0 \to K^-\pi^+$ events have been used to calibrate out detector asymmetries associated with the 'slow pion' in the D^* reconstruction, and care has also been taken to remove the effect of the forward-backward asymmetry coming from the $\gamma - Z$ interference in the e^+e^- annihilation.

In the case that the decays under study involve more than two particles, then the analysis may be extended to consider final state distributions, which can in principle be more sensitive to CPV than the overall rates. BaBar have done this in a comprehensive manner in their $K^+K^-\pi^0$ and $\pi^+\pi^-\pi^0$ study [44], using a variety of techniques to search for differences between D^0 and $\overline{D^0}$ for the Dalitz plots of the final state particles. In four body decays one can pursue analogous methods or study triple-product correlations [40]. A pilot analysis using the latter approach has been performed by FOCUS for the decay $K^+K^-\pi^+\pi^-$ [47]. No signal is yet seen of CPV.

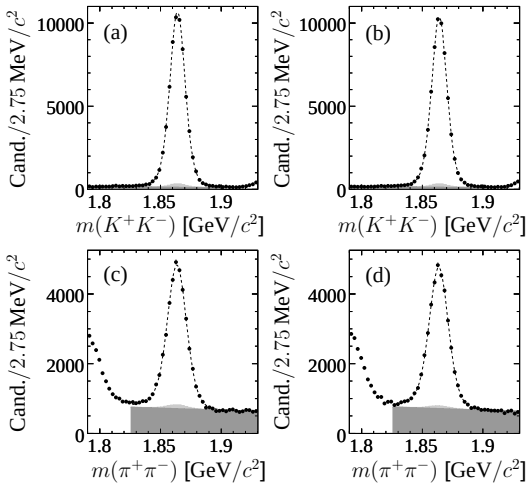

Figure 8: Mass-peaks from BaBar A^f_{CP} analysis [42]. (a) and (b) show the D^0 and $\overline{D^0}$ peaks from the K^+K^- analysis, and (c) and (d) the corresponding peaks from the $\pi^+\pi^-$ analysis. Solid grey indicates non-peaking background; light grey peaking background.

4.2 Rare Charm Decays

The most interesting rare charm decay is the process $D^0 \to \mu^+\mu^-$. In the SM this is extremely suppressed ($\sim 10^{-13}$) but it can be dramatically enhanced in R-parity violating SUSY, which allows for branching ratios up to the level of 10^{-6} [48]. The best existing limit comes from CDF which excludes this decay down to a rate of 4.3×10^{-7} at the 90% C.L. [49] using 360 pb^{-1} of data.

As it the case for the analogous decays in the B sector, radiative and leptonic modes such as $D^0 \to \rho\gamma$, $\mathcal{D}^+ \to \pi^+l^+l^-$ and $D^0 \to \rho l^+l^-$ are of interest. (At the time of writing the only 'rare' decay of this sort which has been observed is the channel $D^0 \to \phi\gamma$, with a branching ratio of $2.5^{+0.7}_{-0.6} \times 10^{-5}$ [50].) In general, however, although new physics contributions can be significantly larger than the SM short-range expectations, it is almost certain that the long-distance contributions are often completely dominant, making the absolute branching ratios an unreliable indicator of beyond-the-SM effects. Nevertheless, many channels hold their interest as the kinematical distributions, such as the dilepton invariant mass, or the forward-backward asymmetry, retain their ability to discriminate between the SM and new physics [48]. An example is provided by the dilepton invariant mass distribution in $D^+ \to \pi^+l^+l^-$ which has recently been proposed [51] as way in which to test whether leptoquarks can be invoked to explained the tension, discussed in Sec. 3.2, between the lattice and experimental determinations of f_{D_s}.

5 Conclusions

After several years of unjust neglect, charm physics is once more recognised as a discipline with a great deal to contribute to the future of HEP. This sea-change has arisen through three unrelated reasons: recent, unexpected, observations in spectroscopy; the realisation that measurements of D decay properties are essential technical inputs in the area of precision CKM physics; and the appreciation, given impetus by the discovery of $D^0 - \overline{D^0}$ mixing, that charm has its own unique discovery potential.

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